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NUV/Blue spectral observations of sprites in the 320-460 nm region: N₂ (2PG) Emissions

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Abstract. A near-ultraviolet (NUV) spectrograph (320-460 nm) was flown on the EXL98 aircraft sprite observation campaign during July 1998. In this wavelength range video rate (60 fields/sec) spectrographic observations found the NUV/blue emissions to be predominantly N₂(2PG). The negligible level of N₂⁺(1NG) present in the spectrum is confirmed by observations of a co-aligned, narrowly filtered 427.8 nm imager and is in agreement with previous ground-based filtered photometer observations. The synthetic spectral fit to the observations indicates a characteristic energy of ~ 1.8 eV, in agreement with our other NUV observations.

Introduction

Sprites are brief (~ 10 ms) optical phenomena that occur above thunderstorms at altitudes between 40-95 km, which have been well documented only during the last two decades [see Sentman, 1998; Sentman *et al.*, 2008]. Broadband, spectral, and filtered photometric observations have been made across the visible wavelengths. Color camera observations show that sprites are primarily red, becoming blue at the lower altitudes [Sentman *et al.*, 1995].

Ground-based spectroscopic measurements of sprites in the optical bandpass of 400-850 nm [Mende *et al.*, 1995; Hampton *et al.*, 1996] show the strongest optical emission from sprites is N₂(1PG), first positive molecular nitrogen emission, which is excited via electron impact. Analysis of red spectral observations estimated a 1 eV Boltzmann electron distribution would produce the observed spectral vibrational distribution

Green *et al.* [1996]. Milikh *et al.* [1997] independently modeled the observed red spectra with similar results. Based on modelling of the red spectral observations of N₂(1PG) emissions, several early predictions of blue emissions in sprites were published [Pasko *et al.*, 1997; Cho and Rycroft, 1998; Morrill *et al.*, 1998; Roussel-Dupré *et al.*, 1998]. More recent modeling efforts have examined other N₂ emissions such as the N₂LBH in the UV [Liu and Pasko, 2005]. These predictions are compared with the reported observations in the discussion section below.

Analysis of one red spectral observation of a sprite required N₂⁺(M) (ionized molecular nitrogen Meinel) emissions for a best fit to the observations [Morrill *et al.*, 1998]. The N₂(1PG) and N₂⁺(M) observations and analysis are the subject of another paper [Bucsela *et al.*, 2003]. Photometric studies of sprites from the ground by Armstrong *et al.* [1998] and Suszcynsky *et al.* [1998] found the blue neutral molecular nitrogen second pos-

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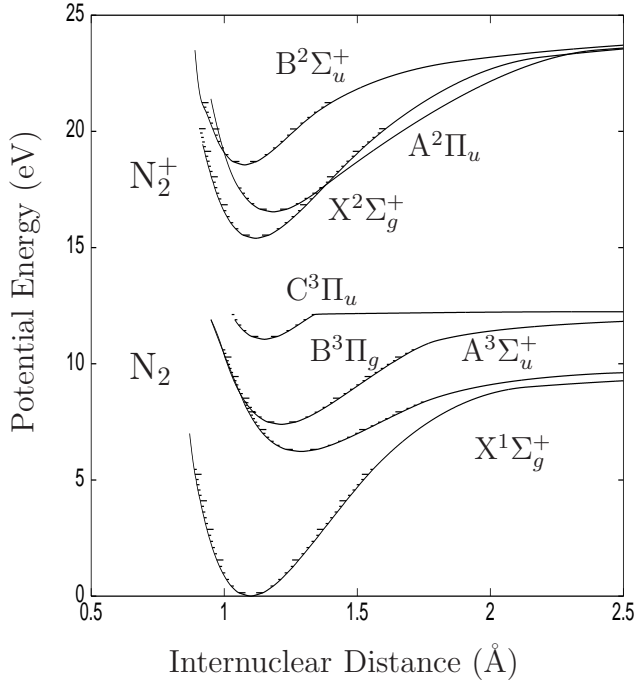


Figure 1. Grottrian Energy Diagram for N_2 , with selected electronic states plotted. The $N_2(1PG)$, $N_2(2PG)$, $N_2^+(1NG)$, and $N_2^+(M)$ transitions are indicated. This figure was made using Tables 80 and 81 from Lofthus and Krupenie [1977].

itive ($N_2(2PG)$) and $N_2^+(1NG)$ are generally of shorter duration (~ 5 ms) than the $N_2(1PG)$ red emissions (which may last up to ~ 100 ms). Furthermore, according to the photometer data, the ionized $N_2^+(1NG)$ are more brief (~ 1 ms) than the $N_2(2PG)$ emissions. In addition to the poor atmospheric transmission in the blue, due to Rayleigh scattering (see Fig. 1 of Morrill *et al.* [1998]), the shorter duration of the blue emissions compared to the red emissions is a factor making blue observations of sprites more difficult. The shorter duration of the blue emissions is simply a factor of the shorter lifetime (nanoseconds rather than microseconds, as shown in Table 1) of the $N_2(C^3\Pi_u)$ and $N_2^+(B^2\Sigma_u^+)$ upper states of the $N_2(2PG)$ and $N_2^+(1NG)$ blue bands. Other recent analysis of space based observations by Kuo *et al.* [2005] has examined 2PG/1NG emission ratios and yield characteristic energies between 4.5 and 6.5 eV.

The primary band systems of molecular nitrogen which lead to near-optical emissions (300-1000 nm) are the $N_2(1PG)$ and $N_2(2PG)$ neutral and the $N_2^+(1NG)$ and $N_2^+(Meinel)$ ionized molecular nitrogen emissions. Table 1 provides an overview of nitrogen and oxygen

optical emissions observed in the aurora. The transitions associated with the nitrogen band systems are the $N_2(B^3\Pi_g) \rightarrow N_2(A^3\Sigma_u^+)$ transition yielding the $N_2(1PG)$ emission, the $N_2(C^3\Pi_u) \rightarrow N_2(B^3\Pi_g)$ transition yielding the $N_2(2PG)$ emission, the $N_2^+(B^2\Sigma_u^+) \rightarrow N_2^+(X^2\Sigma_g^+)$ transition giving the $N_2^+(1NG)$ emission, and the $N_2^+(A^2\Pi_u) \rightarrow N_2^+(X^2\Sigma_g^+)$ transition giving the $N_2^+(Meinel)$ emission. The potential energy curves of both neutral and ionized molecular nitrogen electronic states involved in the above transitions and the ground neutral state are also shown in Fig. 1. The $N_2(2PG)$ and $N_2^+(1NG)$ bands occur at NUV and blue wavelengths (< 450 nm, with brightest emissions < 400 nm), while the $N_2(1PG)$ and $N_2^+(Meinel)$ bands occur at red and near infrared (NIR) wavelengths.

Because of the uncertainties associated with $N_2^+(Meinel)$ quenching and energy transfer, characterization of N_2^+ (ionized molecular nitrogen) is best accomplished by observation of $N_2^+(1NG)$ at shorter wavelengths. One reason for investigating the $N_2(2PG)$ emission rather than the dominant red $N_2(1PG)$ emission is that the upper state of $N_2(1PG)$, $N_2(B^3\Pi_g)$, is partially filled via cascading from the $N_2(C^3\Pi_u)$ state (this cascading is evidence of the $N_2(2PG)$ emissions). Also the $N_2(1PG)$ upper state is more strongly affected by collisional processes than $N_2(2PG)$ [Morrill and Benesch, 1996] complicating the accurate analysis of $N_2(1PG)$. The problems of both cascading and quenching are less severe issues for the $N_2^+(B^2\Sigma_u^+)$ and $N_2(C^3\Pi_u)$ upper electronic states [Morrill and Benesch, 1996]. Additionally, $N_2(1PG)$ has the lowest excitation energy threshold of the four band systems discussed, so emissions from other groups are evidence of higher energy processes. Specifically, from Table 1, the $N_2(1PG)$ threshold energy is 7.5 eV compared to 11.18 eV for $N_2(2PG)$ 18.56 eV for $N_2^+(1NG)$ and 16.54 eV for $N_2^+(M)$.

In this paper we present an analysis of the recent blue spectral observations made during the EXL98 aircraft sprite-observing mission over the U.S. Midwest. Other papers will present further analysis associated with both specific ionization issues and the $N_2(2PG)$ to $N_2^+(1NG)$ ratio [Bucsela *et al.*, 2003; Morrill *et al.*, 2002]. The EXL98 filtered blue imaging of sprites associated with ionized N_2^+ emissions are presented elsewhere [Heavner, 2000].

Instrumentation

The Energetics of Upper Atmospheric Excitation by Lightning (EXL98) campaign was a collaboration between the University of Alaska, Fairbanks (UAF), the

Naval Research Laboratory (NRL), and the Air Force Research Laboratory. This program was designed to investigate the energy budget of middle and upper atmospheric processes excited by lightning using several imaging and photometric observations from a Gulfstream II aircraft. In this paper we present results from a ‘427.8 nm’ filtered imager and a bore mounted unfiltered imager both have a $9.3^\circ \times 7.0^\circ$ field-of-view (FOV) as well as a NUV/Blue spectrograph.

Two imaging instruments were designed specifically to observe neutral $N_2(2PG)$ and ionized $N_2^+(1NG)$ emissions. A Dage/MTI SIT VE1000 camera with a Fuji f/0.7 lens was used to measure images of the $N_2^+(1NG)(0,1)$ band emissions with a narrow passband filter at approximately 427.8 nm. The ‘427.8’ nm filter is a carefully selected filter for observation of $N_2^+(1NG)$. It is a 1.44 nm FWHM filter actually centered at 428.3 nm, specifically selected slightly red of the $N_2(2PG)$ 426.8 nm emissions which would contaminate the filter if it had been centered on 427.8 nm.

A GEN IIUV V53-1845 Video Scope camera and a Lyman Alpha II f/1.7 lens system was optimized for NUV observations. Originally the camera was used as a filtered imager, with a 340.7 nm filter, in order to make observations of $N_2(2PG)$ (neutral) emissions. During the later portion of the campaign, this instrument was refitted as a NUV spectrograph. The NUV spectrograph consisted the GEN IIUV V5301845 Video Scope camera as the detector for light which passed through a Jobin Yvon-Spex CP200 f/2.9 spectrograph and a 133 line/mm grating. The primary input lens focused the incoming light on an 8 mm collimating entrance slit. The slit was oriented horizontally in order to increase the probability of sprite observations. The data was recorded at 60 fields per second and all cameras on aircraft and ground were GPS synchronized providing video images with a common time base to $0.5 \mu s$ or better.

Other instrumentation and the overall EXL98 campaign are described by Siefring *et al.* [2009].

Observation

Sprites observed July 28, 1998 at 06:41:01.278 UT are shown in Fig. 2. The aircraft was flying at an altitude of 14,040 m at a great circle distance of 306 km from the positive cloud-to-ground lightning discharge reported by the National Lightning Detection Network temporally associated with the observed sprite. Fig. 2 (a) is from the unfiltered imager ($9.3^\circ \times 7.0^\circ$ FOV). The horizontal black band indicates the approximate FOV of

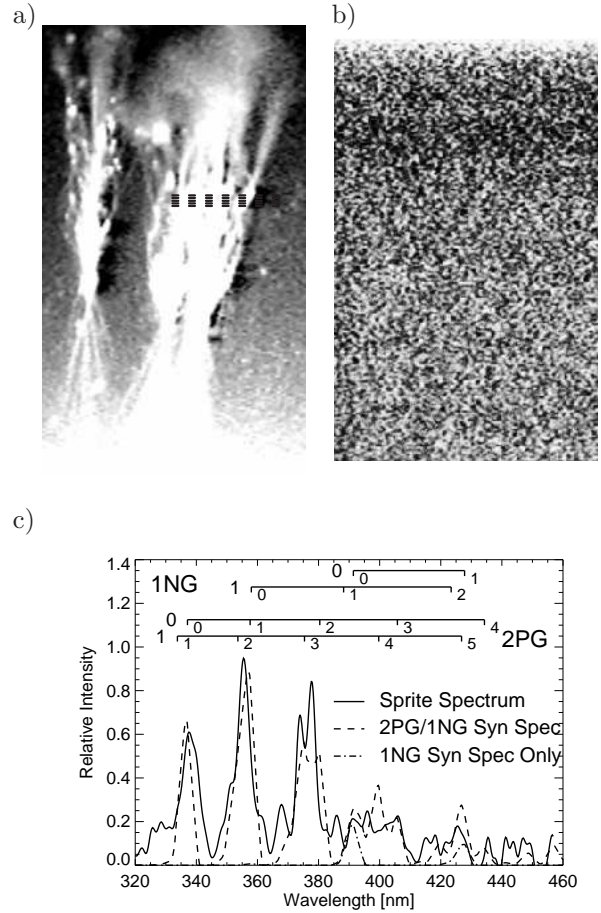


Figure 2. Blue Spectrum of July 28, 1998 06:41:01.278 Sprite. (a) is the broadband image of the sprite with a black dashed line indicating the field of view of the slit spectrograph. (b) is the histogram equalized 427.8 nm filtered imager data. The imager detected no 427.8 nm emissions, agreeing with the lack of any such signature in the spectral observations. (c) shows the spectrum observed by the NUV/Blue spectrograph as the solid line. The dashed line is the synthetic fit to the observations including both neutral $N_2(2PG)$ and ionized $N_2^+(1NG)$. The ionized contribution to the fit is shown as a dash-dot line (primarily near the 391.4 nm and 427.8 nm bands).

the slit in the NUV spectrograph. After gamma correction and background subtraction of the video image of the NUV spectrograph output, three video fields were averaged together for a total time integration of 40 ms (the spectral data were on the upper portion of the scan read-out imager, the time integration only includes a portion of the third field and is not the entire

50 ms of the three fields). The 10 video scan lines over which spectral information was present were also averaged, to improve the signal strength. Fig. 2(c) presents these corrected observations from the NUV spectrograph. The observed spectrum is the solid line while a synthetic spectral fit to the observations modeled with $N_2^+(1NG)$ and $N_2(2PG)$ is shown as a dashed line in Fig. 2(c) (the fit includes corrections for atmospheric transmission using MODTRAN [Morrill *et al.*, 1998] and instrument response). The dotted line in Fig. 2(c) indicates the $N_2^+(1NG)$ contribution to the synthetic fit. The synthetic spectral code used to generate the fit are presented in detail by Bucseli and Sharp [1997]. Specifically, the vibrational distributions were determined by free-fit of the band progressions - adjusted for instrument response and atmospheric transmission - to the spectral data. An assumed rotational temperature of 230K was used, but given the resolution, the fit is not very sensitive to temperature [Bucseli *et al.*, 2003]. Fig. 2(b) is the observation of the sprite from the 427.8 nm filtered imager, which has been histogram equalized to increase the contrast of the image. No indication of $N_2^+(1NG)$ 427.8 nm emissions from the sprite are apparent (in agreement with the spectral fit shown in Fig. 2(c)).

Discussion

Earlier spectral observations near the top of sprites, ~ 65 km, show that the primary optical emission is the $N_2(1PG)$ and here we confirm that the blue component is predominantly $N_2(2PG)$. Any weak molecular ion emission will be short lived and only present in the streamer heads known to makeup these events. EXL98 studies of filtered UV images indicate the $N_2(2PG) / N_2^+(1NG)$ ratio to be of order 4×10^4 in the 65 km region thus confirming the lack of $N_2^+(1NG)$ emission [Morrill *et al.*, 2002]. The current results and our previous UV image ratio results indicate an estimated characteristic energy of ~ 1.8 eV. This reasonably matches the estimated energies in the streamer body from the work of Liu and Pasko [2005]. Specifically, characteristic energy is the average energy of electrons in a weakly ionized gas under an applied electric field. If the gas is collisional the energy distribution is non-Maxwellian. The characteristic energy is the D_e/m_e , where D_e is the electron transverse diffusion coefficient and m_e is the mobility [cf. Raizer, 1991, p 21]. These parameters are derived from laboratory by observing the bulk diffusion and drift in an applied field. Characteristic energies versus electric field for various gas are tabulated in Dutton [1975]. Boltz-

mann solving models of sprites can also report the average/characteristic energy as in Morrill *et al.* [2002]. Pasko *et al.* [1997] did a cross-comparison between more complicated Boltzmann-solving sprite models and those using empirical fits to laboratory data and found generally good agreement between the two methods. These observations are highly time averaged relative to natural sprite time scales and indicate that a significant portion of the observed sprite emission is produced in the body of the streamers. Unfortunately, the averaging of signal over multiple video frames was necessary to achieve significant signal to noise for the synthetic spectral fit. It is important to recognize the different time scales in sprites and related optical emissions—streamers with highly ionized tips most likely create $N_2^+(1NG)$ emissions for sub-1 ms time scales while a longer (10+ ms) $N_2(2PG)$ emission is expected from sprite bodies.

Other studies by Kuo *et al.* [2005] who studies $N_2(2PG) / N_2^+(1NG)$ ratios observed from space derived characteristic energies in the range of 4.5-6.5eV below 60 km or 1.9 to 3.4 times the breakdown field. Our previous observations [Morrill *et al.*, 2002] yielded energies at roughly the breakdown field so are significantly different results which warrant further examination. The 60 km altitude is below our currently observed altitude. Were observations made at this altitude a significant $N_2^+(1NG)$ component would necessarily be present. Additional blue/UV sprite spectral observations with wider altitude range and higher temporal resolution are clearly needed.

Conclusions

We report observations and analysis of the blue/UV sprite spectrum at 65 km altitude. The observed spectrum is well fitted by synthetic spectral code (assuming a 230K rotational temperature) after atmospheric transmission correction and system response correction. The synthetic fit identifies only 2PG emission and implies electron energies of roughly 1.8 eV. This corresponds to similar results from previous studies as well as generally agreeing with other model results for electron energies in streamer bodies in sprites. Because of limitations in temporal resolution and vertical height of the sprites in the reported study, additional blue/NUV observations are needed to confirm these results.

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References

- Armstrong, R. A., J. A. Shorter, M. J. Taylor, D. M. Suszcynsky, W. A. Lyons, and L. S. Jeong, Photometric measurements in the SPRITES '95 & '96 campaigns of nitrogen second positive (399.8 nm) and first negative (427.8 nm) emissions, *J. Atmos. Solar Terr. Physics*, **60**, 787–799, 1998.
- Bucsela, E., J. S. Morrill, M. J. Heavner, C. Seifring, S. Berg, D. Hampton, D. Moudry, E. M. Wescott, and D. Sentman, $N_2(B^3\Pi_g)$ and $N_2^+(A^2\Pi_u)$ vibrational distributions observed in sprites, *J. Atmos. Solar Terr. Physics*, **65**, 583–590, 2003.
- Bucsela, E. J. and W. E. Sharp, NI 8680 and 8629 Å multiplets in the dayglow, *J. Geophys. Res.*, **102**, 2457–2466, 1997.
- Cho, M. and M. J. Rycroft, Computer simulation of the electric field structure and optical emission from cloud-top to the ionosphere, *J. Atmos. Solar Terr. Physics*, **60**(7), 871–888, 1998.
- Dutton, J., A survey of Swarm Data, *J. Phys. Chem. Ref. Data*, pp 577–856, 1975.
- Green, B. D., M. E. Fraser, W. T. Rawlins, L. Jeong, W. A. Blumberg, S. B. Mende, G. R. Swenson, D. L. Hampton, E. M. Wescott, and D. D. Sentman, Molecular excitation in sprites, *Geophys. Res. Lett.*, **23**(23), 2161–2164, 1996.
- Hampton, D. L., M. J. Heavner, E. M. Wescott, and D. D. Sentman, Optical spectral characteristics of sprites, *Geophys. Res. Lett.*, **23**(1), 89–92, 1996.
- Heavner, M. J., *Optical Spectroscopic Observations of Sprites, Blue Jets, and Elves: Inferred Microphysical Processes and Their Macrophysical Implications*, Ph.D. thesis, University of Alaska, Fairbanks, 2000.
- Kuo, C.-L., R. Hsu, A. Chen, H. Su, L. Lee, S. Mende, H. Frey, H. Fukunishi, and Y. Takahashi, Electric fields and electron energies inferred from the usual recorded sprites, *Geophys. Res. Lett.*, **32**, 2005.
- Liu, N. and V. P. Pasko, Molecular nitrogen LBH band system far-UV emissions of sprite streamers, *Geophys. Res. Lett.*, **32**, L05104, 2005, doi:10.1029/2004GL022001.
- Lofthus, A. and P. H. Krupenie, The spectrum of molecular Nitrogen, *J. Phys. Chem. Ref. Data*, **6**(1), 113–307, 1977.
- Mende, S. B., R. L. Rairden, and G. R. Swenson, Sprite spectra: N_2 1PG band identification, *Geophys. Res. Lett.*, **22**, 2633–2636, 1995.
- Milikh, G. M., J. A. Valdivia, and K. Papadopoulos, Model of red sprite optical spectra, *Geophys. Res. Lett.*, **24**(8), 833–836, 1997.
- Morrill, J., E. Bucsela, C. Seifring, M. Heavner, S. Berg, D. Moudry, S. Slinker, R. Fernsler, E. Wescott, D. Sentman, and D. Osborne, Electron energy and electric field estimates in sprites derived from ionized and neutral N_2 emissions, *Geophys. Res. Lett.*, **29**(10), 10.1029/2001GL014018, 2002.
- Morrill, J. S. and W. M. Benesch, Auroral N_2 emissions and the effect of collisional processes on N_2 triplet state vibrational populations, *J. Geophys. Res.*, **101**, 261–274, 1996.
- Morrill, J. S., E. J. Bucsela, V. P. Pasko, S. L. Berg, M. J. Heavner, D. R. Moudry, W. M. Benesch, E. M. Wescott, and D. D. Sentman, Time resolved N_2 triplet state vibrational populations and emissions associated with red sprites, *J. Atmos. Solar Terr. Physics*, **60**, 811–829, 1998.
- Pasko, V. P., U. S. Inan, T. F. Bell, and Y. N. Taranenko, Sprites produced by quasi-electrostatic heating and ionization in the lower ionosphere, *J. Geophys. Res.*, **102**(A3), 4529–4561, 1997.
- Raizer, Y. P., Gas Discharge Physics, Springer-Verlag Berlin Heidelberg, 1991.
- Roussel-Dupré, R., E. Sybaldy, Y. Taranenko, and V. Yukhimuk, Simulations of high-altitude discharges initiated by runaway breakdown, *J. Atmos. Solar Terr. Physics*, **60**(7), 917–940, 1998.
- Sentman, D., Electrical excitation of the middle and upper atmosphere by lightning: Special issue of the Journal of Atmospheric and Solar-Terrestrial Physics, *J. Atmos. Solar Terr. Physics*, **60**(7-9), 667, 1998.
- Sentman, D. D., E. M. Wescott, D. L. Osborne, D. L. Hampton, and M. J. Heavner, Preliminary results from the Sprites94 aircraft campaign: 1. Red Sprites, *Geophys. Res. Lett.*, **22**, 1205–1208, 1995.
- Sentman, D. D., H. C. Stenbaek-Nielsen, M. G. McHard, and J. S. Morrill, Plasma chemistry of sprite streamers, *J. Geophys. Res.*, **113**, D11112, 2008.
- Siefring, C. L., J. S. Morrill, D. D. Sentman, and M. J. Heavner, Simultaneous near-infrared and visible observations of sprites and acoustic gravity waves during the EXL98 campaign, *J. Geophys. Res.*, *this issue*, 2010.
- Suszcynsky, D. M., R. Roussel-Dupré, W. A. Lyons, and R. A. Armstrong, Blue-light imagery and photometry of sprites, *J. Atmos. Solar Terr. Physics*, **60**(7), 801–809, 1998.
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Name	Upper State	Lower State	Lifetime	Quench Altitude	Quench Particle	Threshold Energy
N ₂ (1PG)	N ₂ (B ³ Π _g)	N ₂ (A ³ Σ _u ⁺)	6 μs	53 km	N ₂	7.50 eV
N ₂ (2PG)	N ₂ (C ³ Π _u)	N ₂ (B ³ Π _g)	50 ns	30 km	O ₂	11.18 eV
N ₂ ⁺ (1NG)	N ₂ ⁺ (B ² Σ _u ⁺)	N ₂ ⁺ (X ² Σ _g ⁺)	70 ns	48 km	N ₂ , O ₂	18.56 eV
N ₂ ⁺ (M)	N ₂ ⁺ (A ² Π _u)	N ₂ ⁺ (X ² Σ _g ⁺)	14 μs	85-90 km	N ₂	16.54 eV
N ₂ (VK)	N ₂ (A ³ Σ _u ⁺)	N ₂ (X ¹ Σ _g ⁺)	2 s	145 km	O	6.31 eV
O ₂ ⁺ (1NG)	O ₂ ⁺ b ⁴ Σ	O ₂ ⁺ X ² Π _g	1.2 μs	60 km	N ₂	18.2 eV

Table 1. Atmospheric Species. Several neutral and ionized N₂ and O₂ optical emissions that are observed in the aurora. The earliest spectral observations of sprites identified N₂(1PG) emissions, which are the lowest threshold energy of the N₂ states that emit optically.